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STEEPENED MAGNETOSONIC WAVES IN THE HIGH β PLASMA SURROUNDING COMET GIACOBINI-ZINNER

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ABSTRACT

We extend the previous studies of intense hydromagnetic waves at Giacobini-Zinner to investigate the mode and direction of wave propagation. Simultaneous high-resolution measurements of electron density fluctuations demonstrate that the long period (~ 100 s) waves are propagating in the magnetosonic mode. Principal axis analyses of the long period waves and accompanying partial rotations show that the sum of the wave phase rotations is 360°, indicating that both are parts of the same wave oscillation. From the time sequence of the steepened waveforms observed by ICE, we demonstrate that the waves must propagate towards the Sun with $C_{ph} < V_{sw}$. All available observations are consistent with wave generation by the resonant ion ring or ion beam instability which predicts right-hand polarized waves propagating in the ion beam (solar) direction.

The large amplitudes $\Delta\vec{B}/|B| \sim O(1)$ and small scale sizes (rotational discontinuities) of the cometary waves suggest that rapid pitch-angle scattering and energy transfer with energetic ions should occur. Since the waves are highly compressive, $\Delta|B|/|B| \approx O(0.5)$, one can also anticipate first-order Fermi acceleration.

Keywords: MHD waves, Giacobini-Zinner, ICE, plasma instabilities.

1. INTRODUCTION

High-intensity MHD turbulence as large as 10^4 nT^2/Hz was discovered by the magnetometer and plasma instrument on board the ICE spacecraft over an extended (> 10^6 km) region surrounding comet Giacobini-Zinner (refs. 1-4). Similar turbulence has also been briefly reported as a feature of the solar wind interaction with comet Halley (Refs. 5 and 6) for Sakigake and Giotto observations, respectively.

It is the purpose of this paper to extend the previous work of Tsurutani and Smith (refs. 2-3) by examining simultaneous plasma and field data in an attempt to identify the mode of the long period waves. Additionally, we will discuss the cause and rate of wave steepening and demonstrate how these steepened waves uniquely identify the direction of propagation and the sense of wave polarization in the plasma frame. It will be shown that all available observational evidence is consistent with the long period emissions being right-hand polarized magnetosonic waves generated by the anomalous cyclotron resonance with pick-up ions.

2. OBSERVATIONS

The magnetic field and electron data have been intercompared for the entire encounter interval. It was found that the correlations were often mixed with no obvious or consistent feature readily apparent, with one noticeable exception. At and near the inbound bow wave there was a remarkable correlation between the magnetic field magnitude and plasma density. This is also the region where the waves have their largest amplitudes, are most compressive and most periodic. This is illustrated in Figure 1. Over the interval illustrated, there is a strong correlation between B^2 (and, of course, also B) and N. Increases and decreases in B^2 are accompanied by simultaneous increases and decreases in

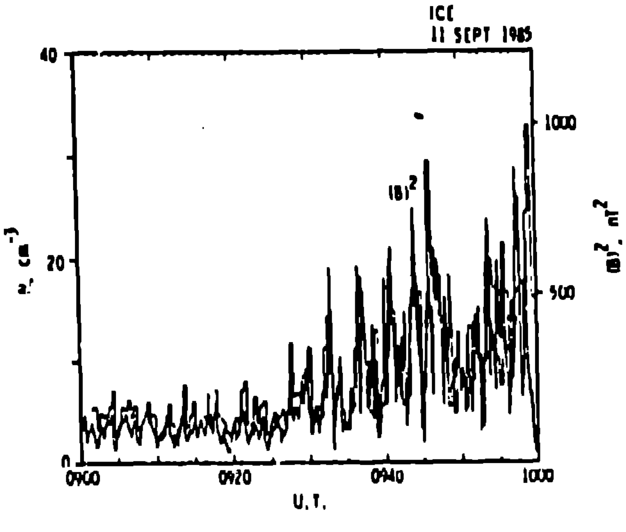

Figure 1. A comparison of the variations in magnetic field magnitude squared (in black) and electron plasma density (in red). For the interval illustrated, the two parameters are strongly correlated, indicating that the fluctuations are fast mode MHD waves.

N. The remarkable correlation between density and magnetic field is consistent with the compressive oscillations of fast-mode waves. It will be shown below that all available observational data supports this interpretation.

The spatial dependence of the cometary waves at Giacobini-Zinner (as discussed in ref. 3) have been investigated. A schematic of the results is illustrated in Figure 2. At large distances (~ 10^6 km) from the comet, the observed magnetic fluctuations are predominantly due to elliptically polarized, long-period hydromagnetic waves (see 0321-0324 UT example at a distance ~ 5.5 x 10^5 km from the nucleus). At these distances, there is little evidence for the presence of high frequency wave packets or partial rotations. At closer distances (~ 3.5 x 10^5 km at 0633-0636 UT), the waves are more compressive and there is a mixture of both partial rotations and high frequency wave packets associated with the magnetic compression of the long period waves. Shown in the upper right of the figure are examples of high frequency wave packets at the wave compressions. This latter interval, 0913-0916 UT, is when ICE was in the bow wave, located at a distance ~ 10^5 km from the comet nucleus (ref. 1). This interval was also illustrated in Figure 1.

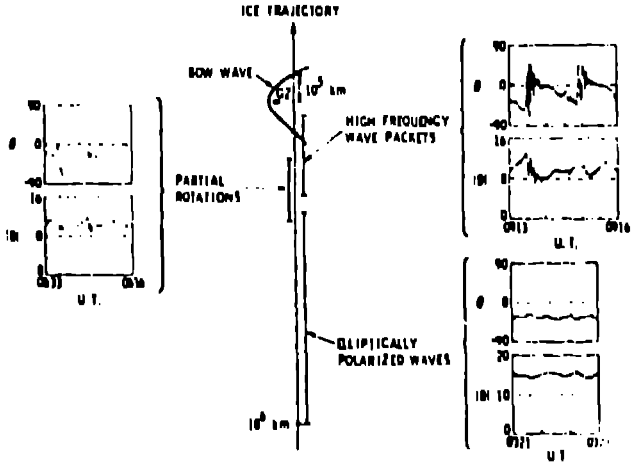

Figure 2. The MHD wave character as a function of distance from the comet. The scale is linear.

High time resolution (3 vectors/s) data were analyzed for the above examples and the results of principal axis analyses (ref. 7) are illustrated in Figure 3. The standard notation of B_1, B_2 and B_3 are used, denoting the field components in the maximum, intermediate and minimum eigenvector directions.

The principal axes projection of a long period wave and a partial rotation at the magnetic compression are illustrated at the top left and central portions of the figures, respectively. The time intervals are 0634:50 to 0635:20 and 0635:20-0635:30 UT, namely two consecutive intervals. From the top panels, it can be seen that the long period wave has a ~ 180° circular rotation and the partial rotation consists of a further 180° rotation in the same sense. Thus the long period wave plus the following partial rotation add up to ~ 360° in rotation. Both rotations are planar (as shown in lower panels).

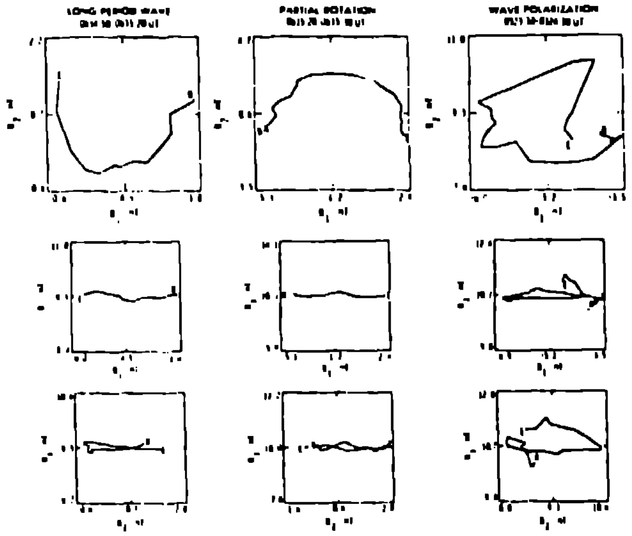

Figure 3. Principal axis analysis results of wave examples shown in figure 2. The left-hand column and central column panels are the principal axis components of a long period wave and of the following partial rotation, respectively. The hodogram at the top shows that each consists of ~ 180° rotations.

2.1 Wave Steepening

Let us first consider the implications of having large amplitude fast-mode waves generated in the plasma. Without additional constraints on the mechanism of wave generation, the waves can, in principle, propagate with velocity C_{ph} either toward or away from the Sun in the plasma frame, as illustrated in Figure 4. In a compressible medium, wave steepening will occur naturally as a direct consequence of the change in wave phase speed C_{ph} due to the presence of large amplitude fluctuations. The rate of steepening is primarily controlled by the density fluctuations $\delta\rho/\rho$, or compressibility of the medium (ref. 8). In the vicinity of the bow wave where $\delta\rho/\rho$ ~ O(1), one can thus expect very rapid steepening for large amplitude compressional waves. Typical steepening lengths are on the order of one wavelength.

To reconcile this anticipated spatial structure in the plasma frame with the temporal structure observed, we must consider four distinct possibilities. The waves can propagate either toward or away from the Sun in the plasma frame at velocities larger or smaller than the solar wind. For fast-mode waves, steepening occurs at the leading edge. Of the four possible temporal signatures shown in Figure 4, only one case (a) is consistent with the observations by ICE, as shown in Figure 5 (see also examples in Figure 2 and ref. 3). Namely, the waves must propagate toward the Sun with $C_{ph} < V_{sw}$. The large amplitude waves detected by ICE must therefore be generated upstream of the spacecraft and subsequently be blown back over it. Furthermore, since $V_{sw} > C_{ph}$, the sense of the observed wave polarization will be opposite to that in the plasma frame. Thus the waves will be right-hand polarized in the plasma frame, consistent with the previous determination that they are magnetosonic in nature.

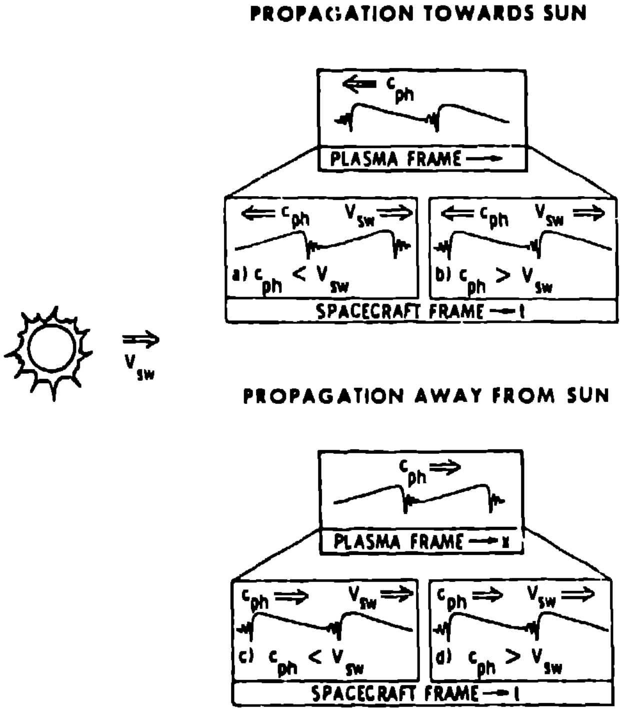

Figure 4. A schematic illustrating several possibilities of wave propagation: a) waves propagating towards the sun in the plasma frame, but are convected in the anti-solar direction in the inertial (spacecraft) frame, b) waves propagating towards the sun in both plasma and inertial frames, c) waves propagating away from the sun where $C_{ph} < V_{sw}$ and d) where $C_{ph} > V_{sw}$. Only one of the four panels is consistent with waves detected by ICE, panel a.

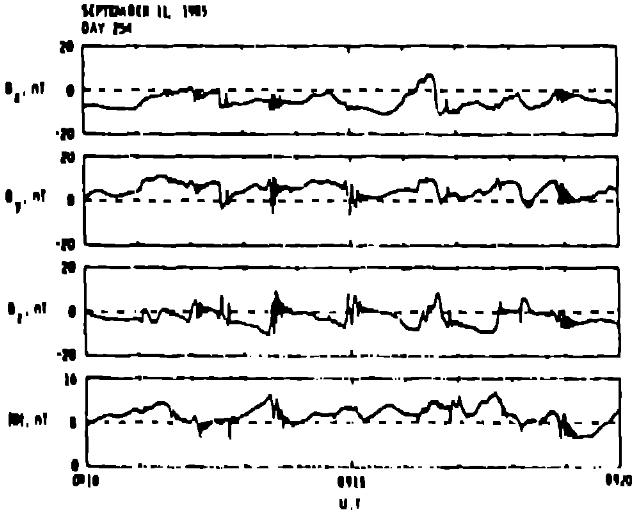

Figure 5. Examples of steepened long period waves and the occurrence of high frequency wave packets or partial rotations at the steepened edges. Note that the wave packets or partial rotations occur at the compressive edge of the long period waves.

The steepening of the compressive hydromagnetic waves at and near the bow wave also offers a natural explanation for the observed polarization of the large amplitude waves as sketched in Figure 6. If the waves are assumed to be basically circularly polarized prior to steepening, the change in phase speed due to the compressive portion of the large amplitude wave will tend to elongate the sinusoidal oscillation into a predominantly "linear portion" followed by a rapid partial rotation at the leading edge of the steepened waves (ref 9).

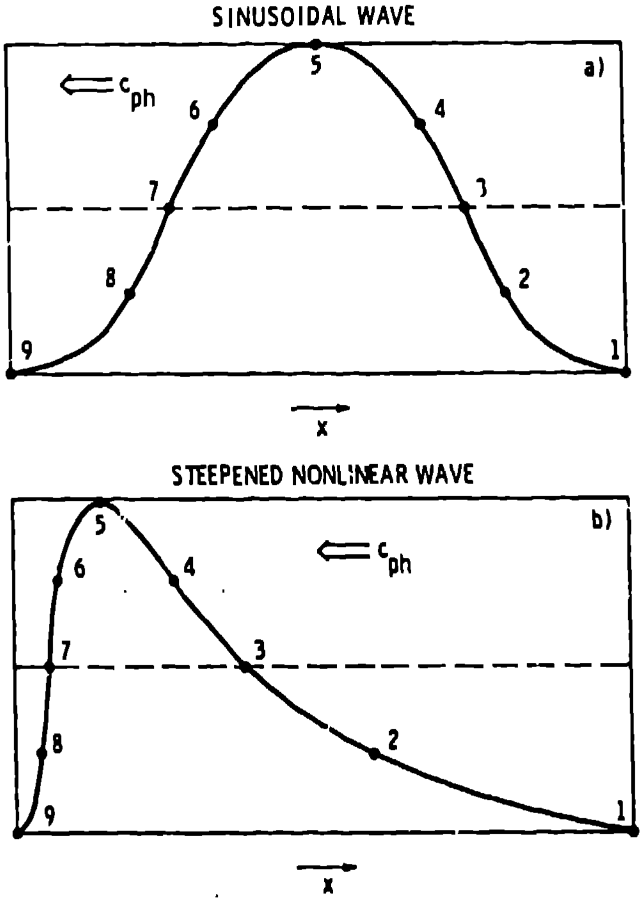

Figure 6. A schematic of an initial sinusoidal wave (panel a) and a nonlinear steepened wave (b). The wave is propagating to the left. The steepened wave appears as a fast phase rotation (rotational discontinuity) followed by a longer-period, slower rotation.

The above is qualitatively consistent with observations. The sense of this rapid rotation determined by analysis of ICE data is always left-handed, but since the wave polarization will be reversed by the rapid solar wind convection ($V_{sw} > C_{ph}$), the waves will be right-hand polarized in the plasma frame. This is also consistent with fast-mode propagation towards the solar direction.

3. SUMMARY AND CONCLUSIONS

The above observations can be explained from a simple model of cometary ion pick-up by the solar wind. For typical interplanetary magnetic field orientations relative to the solar wind velocity ($\alpha = 45°$), the $\overline{V}_{sw} \times \overline{B}$ electric field accelerates the freshly produced ions to moderate kinetic energies. Particles will attain a gyro velocity of $V_{sw} \sin \alpha$ and a parallel velocity of $V_{sw} \cos \alpha$ in the solar wind frame relative to the IMF. This helical beam of ions will be unstable to a resonant gyrating ring instability (refs. 10-13). The waves associated with this resonant instability will have a right-hand sense and will propagate parallel to, but slower than, the ion beam. The waves will therefore have $C_{ph} < V_{sw}$ and be blown back by solar wind convection. The above scenario is consistent with all of the observations presented in this paper.

Steepening of the waves to form a long period "linear" wave and a high frequency partial rotation (rotational discontinuity) was demonstrated to be consistent with fast-mode wave propagation in a high β (~ 2.5) plasma. Near the bow wave, the greatest contribution to the plasma pressure is the hot cometary pick-up ions. Observed wave steepening is well correlated with the expected rate of change of β with increasing distance from the comet.

4. FINAL COMMENTS

We have attempted to better define the cometary MHD wave modes so that space plasma physicists can make further advancements in our understanding of the overall solar wind-comet interaction. Specifically, some of the emerging (future) problems are: 1) a better understanding of the growth, saturation and damping mechanisms of the nonlinear cometary waves. The sink for the enormous wave energy is presently unexplored. 2) Present wave-particle scattering theories do not adequately address particle interactions with nonlinear waves with these characteristics. The waves have large amplitudes ($\Delta\overline{B}/|B| \sim 1$), they are strongly compressive ($\Delta|B|/|B| \sim 0.5$) and the steepened compressive wave fronts have scale sizes much smaller than the cometary ion gyroradii (implying rapid particle scattering). Furthermore, because of nonlinear wave steepening (the leading edge of the wave attains a faster rate of rotation while the trailing portion becomes elongated), particles responsible for generating the waves will soon fall out of resonance. 3) Stochastic Fermi acceleration of energetic particles (both solar wind protons and cometary heavy ions) is probably occurring (refs. 14-15). Besides standard second-order stochastic acceleration, first-order acceleration may be important due to particle interaction with the shock-like (compressive) wave structures. 4) The development of the Kolmogorov-like spectrum (the spectral shape from the H_2O^+ cyclotron peak at 10^{-2} Hz to higher frequencies is relatively smooth and displays a ~ $f^{-5/3}$ dependence) is intriguing and is yet unexplained. Because of the nonlinear nature of many of the above problems, computer simulations may be the best (and possibly only) approach.

5. ACKNOWLEDGMENTS

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